THE DEVELOPMENT OF AN ANALYSES-INTENSIVE SOFTWARE FOR IMPROVED CAMS SYSTEM DESIGN

O.E. Simolowo and O.A. Bamiro
Department of Mechanical Engineering,
University of Ibadan,
Nigeria

ABSTRACT
The computer-aided software developed in this research work is used in designing cam systems by generating various follower motions and cam profiles. It is highly suited for extensive dynamics, kinematics and geometric design analysis based on some inherent features that are unique. The plate cam with either flat-face or roller followers can be designed. Most of the standard and acceptable cam functions are included such as double harmonic, modified trapezoidal, cycloid, 4-5-6 polynomial and others. Various prime circle radii and follower face widths are calculated for flat-face follower design option for any user selected cam angle, follower profile and cam function. Other parameters such as minimum and maximum values of radii of curvature, pressure angle, are also calculated for roller follower design option. In every design the follower motion and cam profiles are calculated and coordinate files can be exported in Cartesian format and automatically imported into a spreadsheet package thereby using all its features for better analysis of results. All dynamic, kinematics and geometric parameters can be plotted and all data may be printed to the screen, to a printer, or to a file.

Keywords: *Cams; Design; software; simulations; validation*

INTRODUCTION
Computer-aided methods are routinely being used in virtually all aspects of engineering today. In some of these cases, computational methods are used to perform kinematic and dynamic analysis of mechanisms in the area of design and manufacturing (Norton, 2000), while strategic planning software packages for manufacturing outfits have been developed using these methods in areas of management decision making and Systems Dy-namics. This research work is geared towards improving the universal design and final commercial production of cams in many automotive and other related companies around the world. A software package for the design and profile simulation of plate cams with a possible choice of two followers using eight standard cam motions for over one hundred and eighty-nine different follower profiles has been developed. The developed software provides the tools to analyze critical aspects of

cam design before physical prototyping or production of such cams and followers, thereby increasing their reliability and performance.

The developed software does not only remove the tedium associated with cam design process but also speeds it up dramatically thereby making the process of comparative design analysis and optimization easier and faster. Some of the unique features of the software that aids better design analysis when compared with others include (i) open-ended choice of cam angular increments (ii) segment by segment application of open-ended choice of increment (iii) made easy and self-explanatory multiple screens (iv) calculations and presentations of results for both radial and linear follower motions.

Cams have been said, over the years, to be easy to design but hard to make (Chen, 1977). This is because various tests must be carried out on the cam systems at the manufacturing stage before their final production; one of such is the profile test for discontinuity. The software developed for the design of cam in this research work has overcome all the problems stated above as various profiles can be synthesized and tested within seconds during the design and manufacturing stages respectively. An initial part of this work was carried out at a preliminary stage (Simolowo, 2004) as depicted in Figure 1. Other works on cams include; dynamic performance of Cams (Norton, 1988); the design of dwell-rise-dwell cams (Brian, 1995); modification of cam type profiles (Gupta and Wiederrich, 1986); optimum design of plate cams (Yoshio and Sarby, 1983); kinematics and dynamics of machinery such as cam systems (Robert, 1988).

NUMERICAL DESIGN OF PLATE CAMS
The diversity of options in cam system design based on the various motion requirements in engineering designs is one of the greatest challenges faced in this area of research. Presented in Figure 1 is the complete option chart defining the entire scope of the cam system design carried out in this work. A design combination of one cam type by two follower types by eight motion segments (consisting of 189 different combinations) by eight-cam functions i.e.1 x 2 x 8 x 8 (128 main combinations) is achieved in this research work.

Flat-Face Follower Cam Design
The output parameters that are peculiar to design of a Plate cam attached to a flat-face follower include (Shigley & Uicker, 1980): prime radius of the cam (Ro), (b) the face Width of follower (Fw), (c) the follower motion profiles and (d) cam coordinates u, v. The equations are given in equations 1 – 4.

$$R_o > \left(\rho_{mni} - y_{max} - y''_{max} \right) \tag{1}$$

$$F_w > y'_{(max)} - y'_{(min)}.. \tag{2}$$

$$u = (R_o + y)\sin\theta + y'\cos(\theta) \tag{3}$$

$$v = (R_o + y)\cos\theta - y'\sin(\theta) \tag{4}$$

Roller Follower Cam Design
The basic design parameters needed (Shigley and Uicker, 1998) as input/output values in the process of the roller follower cam layout are: (a) Pressure angle f. (b) Prime circle radius R_o. (c) Eccentricitye, (d) Radius of the roller follower R_r. (e) Cam coordinates u, v. The equations are given in eq. (5) – (10)

$$\phi = \tan^{-1}\frac{y'-\varepsilon}{\sqrt{Ro^2 - \varepsilon^2 + y}} \tag{5}$$

$$R_o = \left(\left[\frac{y'-\varepsilon - y(\tan\theta)}{\tan\theta} \right]^2 + \varepsilon^2 \right)^{\frac{1}{2}} \tag{6}$$

$$r_{pitch} = r_{min} + R_r \tag{7}$$

$$\rho_{pitch} = \rho_{min} + R_r = \frac{\left[(R_o+y)^2 + (y')^2 \right]^{3/2}}{\left[(R_o+y)^2 + 2(y')^2 - (R_o+y)y'' \right]} \tag{8}$$

$$u = \left(\sqrt{R_o - \varepsilon^2} + y \right)\sin\theta + \varepsilon\cos\theta + R_r\sin(\phi - \theta) \tag{9}$$

$$v = \left(\sqrt{R_o - \varepsilon^2} + y \right)\sin\theta - \varepsilon\cos\theta - R_r\sin(\phi - \theta) \tag{10}$$

where f is the pressure angle given by equation (5).

DEVELOPMENT OF SOFTWARE

New features were introduced in the software developed presently as compared with some of the features that exist in most of the widely used software packages for the commercial design of cams systems. Table 1 summarises these features and compares them with those in some existing software. The descriptions of operations carried out to bring about these features are presented in the section below:

Software Features

Limitless choice of angular increment and its application to all motion segments

To accomplish this, a disjoint algorithm architecture approach was used in the development of the software. This method entailed;

i) breaking the whole program algorithm into disjoint modules and performing simulations for these separate modules.

ii) Enabling all the separate motion segments to accept any prescribed value of input parameters such as cam angular increment (q) and other parameters considered under the section on numerical design.

Simulation results generated for both radial and linear motions

The follower displacements and their derivatives $y, y', and y''$ such as presented for double harmonic motion and modified trapezoidal cam functions (equations 11-24) were computed by considering

i) angular cam rotation in radians (q)

ii) angular speed of the cam (w). All simulations were carried out and results presented for the two motion types. The final motion and cam profiles generated are however exactly the same for the motions.

Simplified designs on increased interface

The operation leading to this feature is the employment of the multiple executable form selection method at both input and design stages of the software development. For each segment of the follower motion there are 2-3 input interfaces and 3-4 design output interfaces. This method involves

i) even distribution of minimal design parameters on different executable forms;

ii) comprehensive interactive programming on sequential interfaces. These attributes make the software more users friendly when compared with the single or dual interfaces that are overcrowded with design parameters and procedures as found in existing software.

The developed software is able to design for all the choices depicted in Figure 1. These involve the following:

1. Cam Type: Plate cams as commonly used in reciprocating internal combustion engines.
2. Follower Type: Flat-face and Roller
3. Relative follower/cam motion: Reciprocating.
4. **Cam motions: Eight different cam motions.**
5. **Follower motions: 8-motion segments with a total of 190 different combinations.**

The task of developing program codes using a versatile visual programming language (Evangelos, 2002; Byron, 2004) for the design of flat-face and roller follower cams entailed the following:

1. Generation of $y, y', and y''$: The codes were written using equations (11) – (24) and those for other standard cam motions considered in the software

2. Generation of u, and v values: Equations (3) and (4) were used in generating the geometric coordinates for flat-face follower, while (9) and (10) were used for roller follower

3. Determination of maximum and minimum values of $y, y', and y''$: The computer program was made to determine these values from those generated in step (1) above

4. Determination of R_o, (flat-face follower) F_w, Rr, f, r_{pitch} R_o, (roller follower) and rmin: All these parameters were calculated using com-
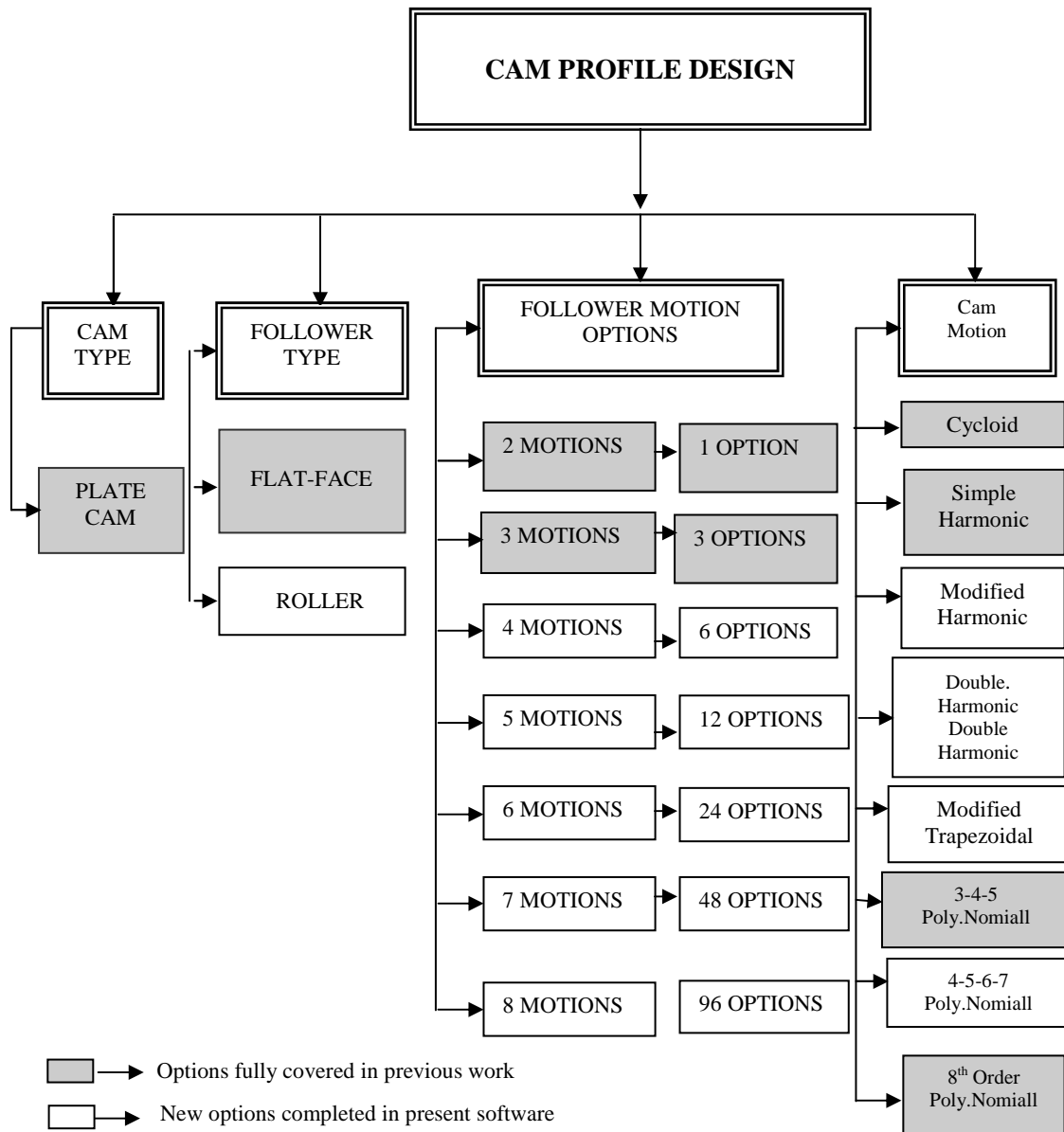
Fig. 1: Design Options for Developed Software

puter codes employing equations (1), (2), (5), (6), (7) and (8) accordingly

5. Cartesian plotting of *y, y', and y″* and generation of cam profile: Program codes were written to automatically export numerical value generated to a spread sheet application and then plotted while within the software.

RESULTS VALIDATION AND DESIGN SIMULATIONS

Sample simulations were carried out for both the flat-face and roller follower options using the developed software. For the flat-face design simulation a 3-follower-motion segment (R-R-D) was considered. The double harmonic cam motion was applied to the rise and return motions while the same 5° increment was used in the 3 different segments for the determination of the design output parameters. In the application of the

software for the design of the roller follower cam, a 2-follower motion-segment was selected. However, in this case, two different cam functions were chosen for the rise and return motion segments namely, the modified harmonic and cycloid motions respectively.

Shown in Tables 2 and 3 are the input parameters for the simulations while equations (11) - (24) are the cam motions for double harmonic, modified trapezoidal and cycloid (Norton, 1998) used in the above sample simulations. The numeric results for the standard sample simulations carried out using the software are presented in Tables 4 and 5. Also presented in Figures 2-5 are the motion and cam profiles of the sample designs. It is observed in the profiles of the two sample designs that there are no discontinuities in the velocity or acceleration graphs. This implies that the two designs could be used for high speed applications.

Table 1: Improved Features of developed software against features of widely used software

No.	Features Of Existing Commercial Software	Improvement In Present Software
1	Limited number of choices of cam angle increment	Limitless choice of angular increments
2	Application of the limited cam angular increments to the overall design of cam systems	Application of limitless choice of cam angle increments to every particular motion-segment
3	Presentation of motion derivatives results in only one type of motion (linear or radial dimensions)	Presentation of motion derivatives results in both linear and radial dimensions
4	Numerous and multiple designs on fewer interfaces	Simplified and less cumbersome designs on increased interfaces

Table 2: Design Input Parameters for Flat-Face Follower Option

Segments	Foll. Motion	Cam motion	Cam angle (deg.)	Initial lift (mm)	Final Lift (mm)	Increment (deg)
1	Rise	D.Harmonic	100°	0 mm	25mm	5°
2	Return	D.Harmonic	200°	25mm	0mm	5°
3	Dwell		360°	0mm	0mm	5°

Table 3:   Design Input Parameters for Roller Follower Option

Seg-ments	Foll. Motion	Cam motion	Cam angle (deg)	Initial lift (mm)	Final Lift (mm)	Increment (deg)	R_r (mm)	R_o (mm)	P_{max} degrees	Ecc (mm)
1	Rise	M.Trap	100	0	10	10				
2	Return	Cycloid	360	10	0	10	1.00	16.53	30	1.5

Table 4:   Design Output Parameters for Flat-Face Follower Option

Parameter	y' (mm/rad)	y'' (mm/rad^2)	R_o (mm)	F_w (mm)
Minimum	-29.14	-81.00		
Maximum	29.14	45.28	64.00	60.00

Table 5:   Design Output Parameters for Roller Follower Option

Segment	Follower Motion		Radius of Curvature (mm)	Pressure angle (mm)	Roller radius (mm)
1	Rise	Maximum	49.40	19.80	12.68
		Minimum	-75.29	0.086	1.50
2	Return	Maximum	17.79	15.82	16.52
		Minimum	8.50	3.38	2.87

Table 6:-Design Input Parameters for Validation Process

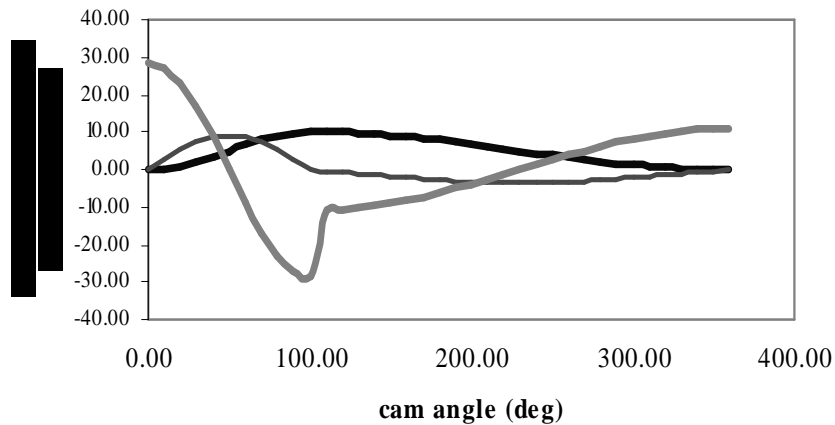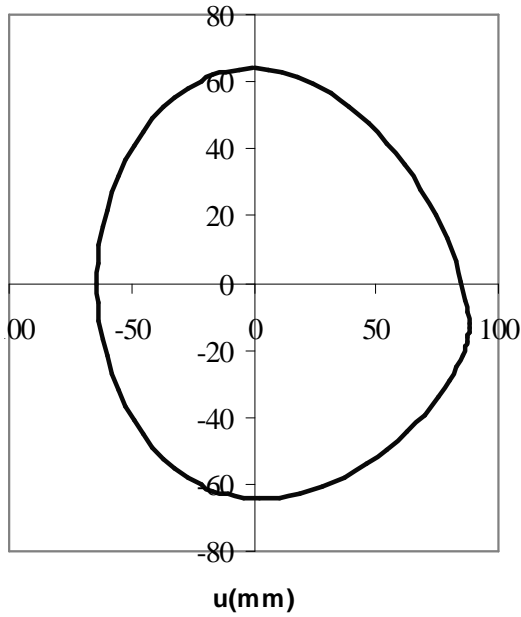| Segments	Foll. motion	Cam motion	Cam angle	Initial lift	Final Lift	Increment	Cam rotation
1	Rise	S.H.M	100°	10mm	10mm	1°	
2	Return	S.H.M	360°	10mm	0mm	1°	1 rpm

Fig. 2: - Follower profiles for Sample Flat-face Follower cam Design

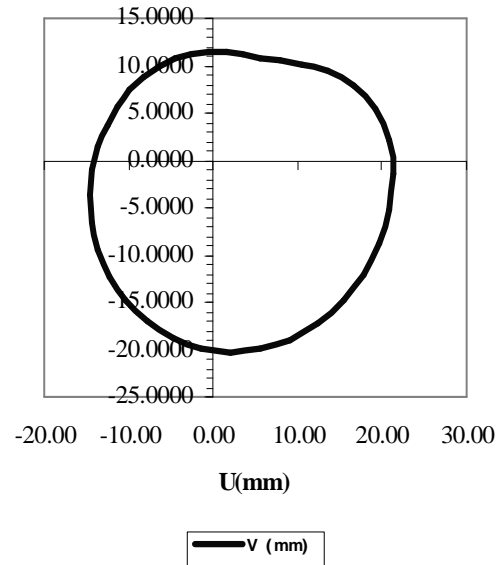**Fig. 3: Cam Profile for Sample Flat-face Follower cam Design**

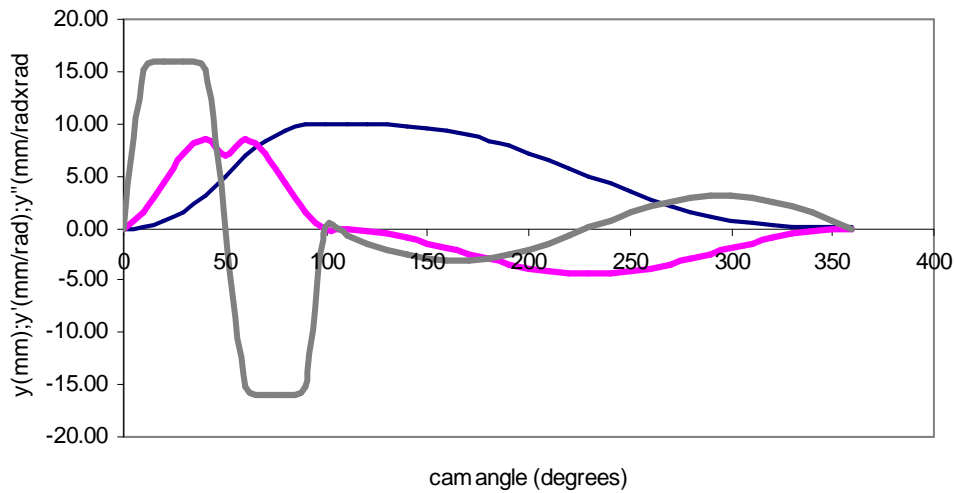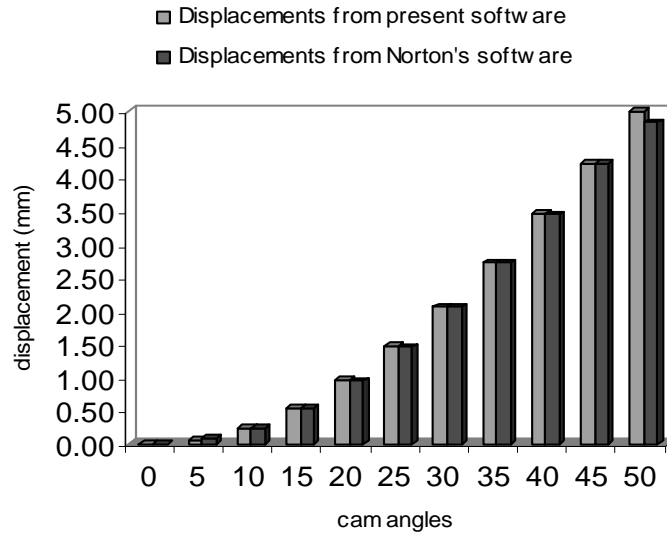
Fig. 5: -   Cam Profiles for Sample Roller Follower Cam Design

cam angle (degrees)

Fig. 4: - Follower Profiles For Sample Roller Follower Cam

■ Displacements from present softw are

■ Displacements from Norton's softw are

Fig. 6: –Y Values for rise motion: Developed Software vs. Norton's Software

■ Displacements from present softw are

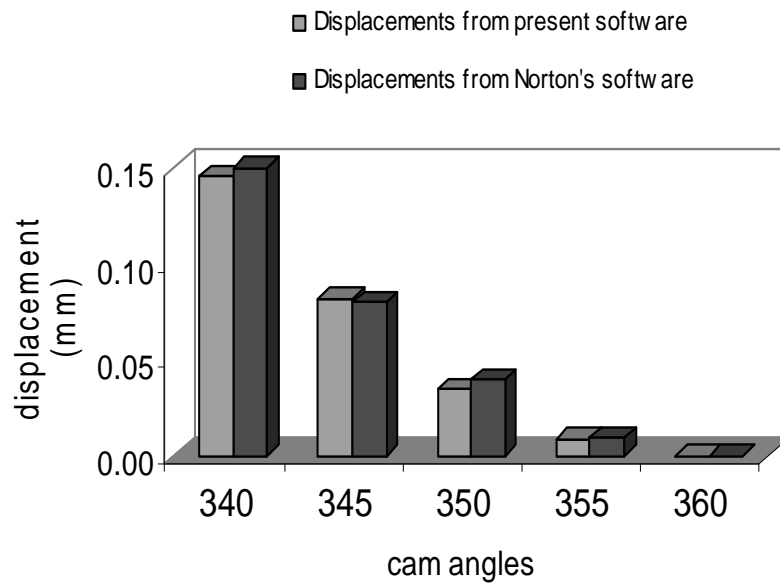■ Displacements from Norton's softw are

Fig.7: –Y Values for return motion: Developed Software vs. Norton's Software
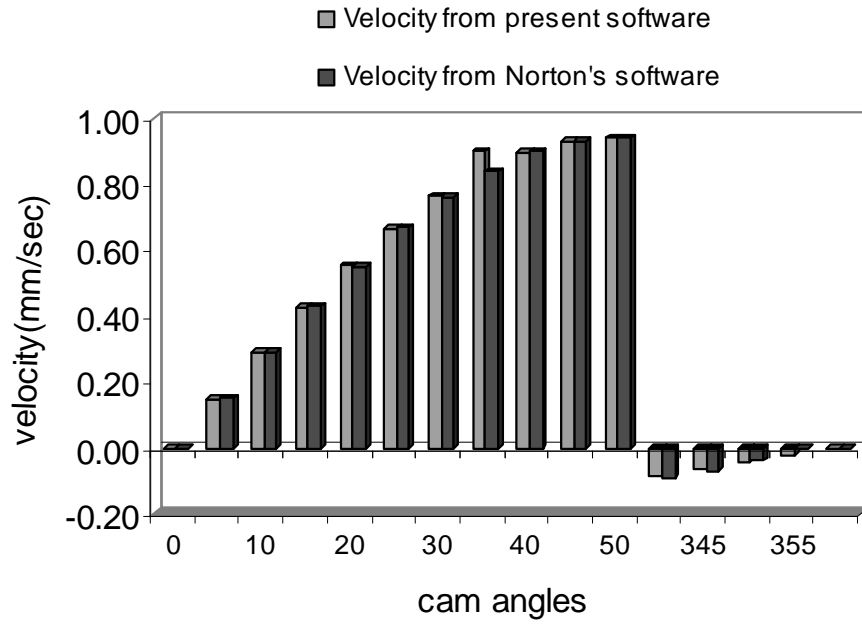
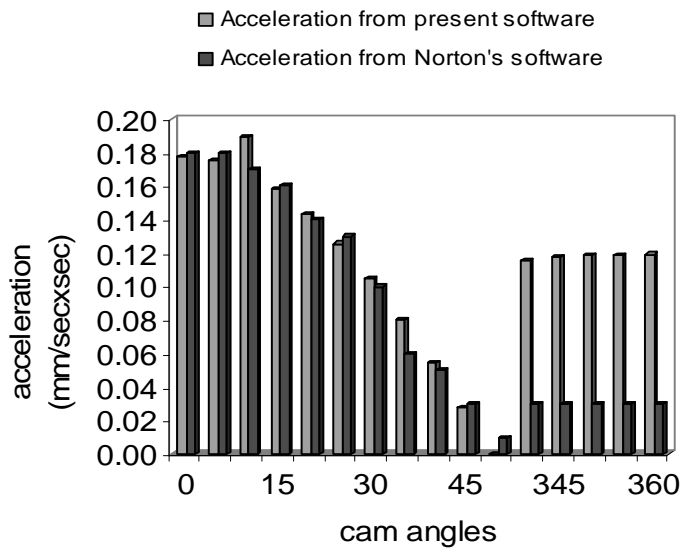Fig. 8: –Y$^{|}$ Values: Developed Software vs. Norton's Software

Fig. 9: –Y$^{||}$ Values: Developed Software vs. Norton's Software

Double Harmonic Motion: Rise

$$Y = \frac{L}{2}\left\{\left[1 - \cos\left(\pi\frac{\theta}{\beta}\right)\right] - \frac{1}{4}\left[1 - \cos\left(2\pi\frac{\theta}{\beta}\right)\right]\right\}$$

$$Y' = \frac{\pi}{\beta}\frac{L}{2}\left\{\left[\sin\left(\pi\frac{\theta}{\beta}\right)\right] - \frac{1}{2}\left[\sin\left(2\pi\frac{\theta}{\beta}\right)\right]\right\} \quad (11)$$

$$Y'' = \frac{\pi^2}{\beta^2}\frac{L}{2}\left\{\left[\cos\left(\pi\frac{\theta}{\beta}\right)\right] - \left[\cos\left(2\pi\frac{\theta}{\beta}\right)\right]\right\}$$

Double Harmonic Motion: Return

$$Y = \frac{h}{2}\left\{\left[1 + \cos\left(\pi\frac{\theta}{\beta}\right)\right] - \frac{1}{4}\left[1 - \cos\left(2\pi\frac{\theta}{\beta}\right)\right]\right\}$$

$$Y' = -\frac{\pi}{\beta}\frac{h}{2}\left\{\left[\sin\left(\pi\frac{\theta}{\beta}\right)\right] + \frac{1}{2}\left[\sin\left(2\pi\frac{\theta}{\beta}\right)\right]\right\}$$

$$(12)$$

$$Y'' = -\frac{\pi^2}{\beta^2}\frac{h}{2}\left\{\left[\cos\left(\pi\frac{\theta}{\beta}\right)\right] + \left[\cos\left(2\pi\frac{\theta}{\beta}\right)\right]\right\}$$

Modified Trapezoidal Motion: Rise

For $\quad 0\beta \le \theta \le \frac{1}{8}\beta$

$$Y = L\left[0.38898448\ \frac{\theta}{\beta} - 0.0309544\mathrm{s}\ \mathrm{in}\left(4\pi\frac{\theta}{\beta}\right)\right]$$

$$Y' = 0.38898448\ \frac{L}{\beta}\left[1 - \cos\left(4\pi\frac{\theta}{\beta}\right)\right] \quad (13)$$

$$Y'' = 4.888124\ \frac{L}{\beta}\sin\left(4\pi\frac{\theta}{\beta}\right)$$

For $\quad \frac{1}{8}\beta \le \theta \le \frac{3}{8}\beta$

$$Y = L\left[2.4406184\left(\frac{\theta}{\beta}\right)^2 - 0.22203097\left(\frac{\theta}{\beta}\right) + 0.00723407\right]$$

$$Y' = \frac{L}{\beta}\left[4.888124\ \left(\frac{\theta}{\beta}\right) - 0.22203097\ \right] \quad (14)$$

$$Y'' = 4.888124\ \frac{L}{\beta^2}$$

For $\quad \frac{3}{8}\beta \le \theta \le \frac{5}{8}\beta$

$$Y = L\left[1.6110154\frac{\theta}{\beta} - 0.0309544\sin\left(4\pi\frac{\theta}{\beta} - \pi\right) - .3055077\right]$$

$$Y'' = \frac{L}{\beta}\left[1.6110154 + .38898448\cos\left(4\pi\frac{\theta}{\beta} - \pi\right)\right]$$

$$(15)$$

$$Y'' = 4.888124\frac{L}{\beta^2}\sin\left(4\pi\frac{\theta}{\beta} - \pi\right)$$

For $\quad \frac{5}{8}\beta \le \theta \le \frac{7}{8}\beta,$

$$Y = L\left[-2.4406184\left(\frac{\theta}{\beta}\right)^2 + 4.6660917\left(\frac{\theta}{\beta}\right) - 1.2292648\right]$$

$$Y' = \frac{L}{\beta}\left[-4.888124\ \left(\frac{\theta}{\beta}\right) + 4.6660917\ \right] \quad (16)$$

$$Y'' = -4.888124\frac{L}{\beta^2}$$

For $\quad \frac{7}{8}\beta \le \theta \le \beta$

$$Y = L\left[0.6110154 - 0.38898448\frac{\theta}{\beta} - .0309544\sin\left(4\pi\frac{\theta}{\beta} - 3\pi\right)\right]$$

$$Y' = 0.38898448\ \frac{L}{\beta}\left[1 + \cos\left(4\pi\frac{\theta}{\beta} - 3\pi\right)\right]$$

$$(17)$$

$$Y'' = -4.888124\ \frac{L}{\beta^2}\sin\left(4\pi\frac{\theta}{\beta} - 3\pi\right)$$

Modified Trapezoidal Motion: Return:

For $\quad 0\beta \le \theta \le \frac{1}{8}\beta$

$$Y = L\left[1.0 - 0.38898448\ \frac{\theta}{\beta} - 0.0309544\mathrm{s}\ \mathrm{in}\left(4\pi\frac{\theta}{\beta}\right)\right]$$

$$Y' = -0.38898448\ \frac{L}{\beta}\left[1 - \cos\left(4\pi\frac{\theta}{\beta}\right)\right] \quad (18)$$

$$Y'' = -4.888124\frac{L}{\beta}\sin\left(4\pi\frac{\theta}{\beta}\right)$$

For $\quad \frac{1}{8}\beta \le \theta \le \frac{3}{8}\beta$

$$Y = L\left[1.0 - 2.4406184\ \left(\frac{\theta}{\beta}\right)^2 - 0.22203097\ \left(\frac{\theta}{\beta}\right) + 0.00723407\ \right]$$

$$Y' = -\frac{L}{\beta}\left[4.888124\left(\frac{\theta}{\beta}\right) - 0.22203097\right] \quad (19)$$

$$Y'' = -4.888124\frac{L}{\beta^2}$$

For $\frac{3}{8}\beta \leq \theta \leq \frac{5}{8}\beta$

$$Y = L\left[1.0 - 1.6110154\frac{\theta}{\beta} - 0.0309544\sin\left(4\pi\frac{\theta}{\beta} - \pi\right) - .3055077\right]$$

$$Y'' = -\frac{L}{\beta}\left[1.6110154 + .38898448\cos\left(4\pi\frac{\theta}{\beta} - \pi\right)\right] \quad (20)$$

$$Y'' = -4.888124\ \frac{L}{\beta^2}\sin\left(4\pi\ \frac{\theta}{\beta} - \pi\right)$$

For $\frac{5}{8}\beta \leq \theta \leq \frac{7}{8}\beta$,

$$Y = L\left[1.0 - 2.4406184\left(\frac{\theta}{\beta}\right)^2 + 4.6660917\left(\frac{\theta}{\beta}\right) - 1.2292648\right]$$

$$Y' = -\frac{L}{\beta}\left[-4.888124\left(\frac{\theta}{\beta}\right) + 4.6660917\right] \quad (21)$$

$$Y'' = 4.888124\ \frac{L}{\beta^2}$$

For $\frac{7}{8}\beta \leq \theta \leq \beta$

$$Y = L\left[1.0 - 0.6110154 - 0.38898448\ \frac{\theta}{\beta} - .0309544\sin\left(4\pi\frac{\theta}{\beta} - 3\pi\right)\right]$$

$$Y' = -0.38898448\ \frac{L}{\beta}\left[1 + \cos\left(4\pi\ \frac{\theta}{\beta} - 3\pi\right)\right] \quad (22)$$

$$Y'' = 4.888124\ \frac{L}{\beta^2}\sin\left(4\pi\ \frac{\theta}{\beta} - 3\pi\right)$$

Cycloid – Motion: Rise

$$Y = L\left(\frac{\theta}{\beta} - \frac{1}{2\pi}\sin\frac{2\pi\theta}{\beta}\right)$$

$$Y^i = \frac{L}{\beta}\left(1 - \cos\frac{2\pi\theta}{\beta}\right) \quad (23)$$

$$Y^{ii} = \frac{2\pi L}{\beta^2}\sin\frac{2\pi\theta}{\beta}$$

Cycloid – Motion: Return

$$Y = L\left(1 - \frac{\theta}{\beta} + \frac{1}{2\pi}\sin\frac{2\pi\theta}{\beta}\right)$$

$$Y^i = -\frac{L}{\beta}\left(1 - \cos\frac{2\pi\theta}{\beta}\right)$$

$$Y^{ii} = -\frac{2\pi L}{\beta^2}\sin\frac{2\pi\theta}{\beta} \quad 24)$$

A case study sample simulation was considered in the validation of the software being developed. It involved a 2-follower motion segment design (R-R) using the simple harmonic motion presented in equation (25 - 26) for both segments. The demonstration version of Dynacam, a widely used commercial software package was downloaded (Norton, 2000) and used in the validation process. The choice of case study simulations covers the rise and fall follower motions and double harmonic cam motion. The same set of design parameters were input to the research software as well as the newly-downloaded demonstration version of Dynacam. Output results such as displacements, velocities and accelerations were compared for the two software packages using the same increment of cam angles namely, 0°, 5°, 10°, 15°, 20°, 25°, 30°, 35°, 40°, 45°, 50°, 340°, 345°, 350°, 355° and 360°. Shown in Table 6 and Figure 7 respectively are the input parameters and result obtained for the validation process.

The results obtained from the two software show that the values of displacements, velocities and accelerations generated for the same set of input values are exactly the same except for some acceleration values presented in Figure 8. This may be because of rounding up the different places of decimals at various computing stages in the two software packages. While the developed software gives its result in exponential form to about 13 places of decimals, Norton's software considers only 2 places of decimals. The other critical parameters such R_o, F_w, U and V are obtained from the extreme values of the displacement and its derivatives.

The Dynacam uses terms such as motion, program, position and delta theta to represent follower motion, cam motion, Lift and angular increment respectively in the developed software. Furthermore, the developed software has increments with any possible value within range of cam angles and for different motion segments. However, Dynacam has only one delta theta for all the segments with the possibility of only three different values (1°, 0.5^o and 0.25^o). The Dynacam software

presents its results for displacement, velocity and acceleration in mm, mm/s and mm/s^2 respectively. However, to make the research software being developed more universal; its results are presented both in mm/sec, mm/sec^2, rad/sec and rad/sec^2. The part that corresponds to that of the Dynacam (mm, mm/s and mm/s^2) has been used in this validation.

Simple-Harmonic-Motion: Rise

$$Y = \frac{L}{2}\left(1 - \cos\frac{\pi\theta}{\beta}\right)$$

$$Y' = \frac{\pi L}{2\beta}\sin\frac{\pi\theta}{\beta}$$

$$Y^{ii} = \frac{\pi^2 L}{2\beta^2}\cos\frac{\pi\theta}{\beta} \qquad (25)$$

$$Y^{ii} = \frac{\pi^2 L}{2\beta^2}\cos\frac{\pi\theta}{\beta}$$

Simple-Harmonic-Motion: Return

$$Y = \frac{L}{2}\left(1 + \cos\frac{\pi\theta}{\beta}\right)$$

$$Y' = -\frac{\pi L}{2\beta}\sin\frac{\pi\theta}{\beta}$$

$$Y^{ii} = -\frac{\pi^2 L}{2\beta^2}\cos\frac{\pi\theta}{\beta} \qquad (26)$$

CONCLUSION

A Computer-Aided Design (CAD) package that can be used to assist cam designers and manufacturers in designing cams in lesser time has been developed. The software is configured to give better design analysis and to generate profiles that finally converge to good cams having smooth dynamics at their operating speeds. The many design combinations, repetition of calculations coupled with plotting of hundreds of cam and follower profile points involved in cam systems design has justified the need for the development of the software. The software design algorithm

entailed the use of standard trigonometric and polynomial cam functions in simulating the follower motion derivatives; determining the follower and cam design parameters; generating the cam coordinates; and finally drawing the follower motions and cam profiles. The software has the capability of generating various profiles of plate cams and follower motions for a selection combination (1x2x1x8x190) i.e. one cam type (plate), two follower types (flat-face and roller), one follower/frame motion (reciprocating), eight cam motions (cycloid, simple harmonic, double harmonic, modified trapezoidal, modified harmonic, 3-4-5 polynomial, 4-5-6 polynomial and 8th order polynomial), 190 different follower motions (for a total of 8-motion segments).

Among some of the common features of the developed software, there are some unique ones that make it different from all others. They include; (i) open-ended degree increment in drawing all the cam and follower profiles and in calculating all design parameters (ii) segment by segment application of the open-ended degree increment in generating cam and follower profiles and determination of other values (iii) presentation of design results to include the rotational and linear dimensions for all follower motions and its derivatives.

NOMENCLATURE

R_o : Prime circle radius
F_w.   : Follower face width
$\{U, V\}$: Coordinates of the contact point in a coordinate system attached to the cam
Y : Displacement of follower with respect to q
Y' : First derivatives of displacement of follower with respect to q
Y'' : Second derivatives of displacement of follower with respect to q
r : Distance of the instantaneous center of curvature to the cam center
L : Maximum displacement of follower (lift)
R_r : Radius of follower roller

Greek symbols
β : Cam angle interval for motion segments
ε : Offset of the follower face

θ :   Angle of cam rotation

ρ :   Radius of curvature of the current contact point of cam and   follower

r_{Pitch} :   Radius of curvature of pitch curve

$\{f_{Max/min}\}$:   Maximum and minimum Pressure angle

r_{min} :   Minimum radius of curvature

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